
Instrumenting CPython with DTrace and SystemTap

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DTrace and SystemTap are monitoring tools, each providing a way to inspect what the processes on a computer system are doing. They both use domain-specific languages allowing a user to write scripts which:

- filter which processes are to be observed
- gather data from the processes of interest
- generate reports on the data

As of Python 3.6, CPython can be built with embedded “markers”, also known as “probes”, that can be observed by a DTrace or SystemTap script, making it easier to monitor what the CPython processes on a system are doing.

CPython implementation detail: DTrace markers are implementation details of the CPython interpreter. No guarantees are made about probe compatibility between versions of CPython. DTrace scripts can stop working or work incorrectly without warning when changing CPython versions.

1 Enabling the static markers

macOS comes with built-in support for DTrace. On Linux, in order to build CPython with the embedded markers for SystemTap, the SystemTap development tools must be installed.

On a Linux machine, this can be done via:

```
$ yum install systemtap-sdt-devel
```

or:

```
$ sudo apt-get install systemtap-sdt-dev
```

CPython must then be configured with the `--with-dtrace` option:

```
checking for --with-dtrace... yes
```

On macOS, you can list available DTrace probes by running a Python process in the background and listing all probes made available by the Python provider:

```
$ python3.6 -q &
$ sudo dtrace -l -P python$! # or: dtrace -l -m python3.6
```

ID	PROVIDER	MODULE	FUNCTION NAME
29564	python18035	python3.6	_PyEval_EvalFrameDefault function-entry
29565	python18035	python3.6	dtrace_function_entry function-entry
29566	python18035	python3.6	_PyEval_EvalFrameDefault function-
↪return			
29567	python18035	python3.6	dtrace_function_return function-
↪return			
29568	python18035	python3.6	collect gc-done
29569	python18035	python3.6	collect gc-start
29570	python18035	python3.6	_PyEval_EvalFrameDefault line
29571	python18035	python3.6	maybe_dtrace_line line

On Linux, you can verify if the SystemTap static markers are present in the built binary by seeing if it contains a “.note.stapsdt” section.

```
$ readelf -S ./python | grep .note.stapsdt
[30] .note.stapsdt          NOTE              0000000000000000 00308d78
```

If you’ve built Python as a shared library (with the `--enable-shared` configure option), you need to look instead within the shared library. For example:

```
$ readelf -S libpython3.3dm.so.1.0 | grep .note.stapsdt
[29] .note.stapsdt          NOTE              0000000000000000 00365b68
```

Sufficiently modern readelf can print the metadata:

```
$ readelf -n ./python
```

Displaying notes found at file offset 0x00000254 with length 0x00000020:

Owner	Data size	Description
GNU	0x00000010	NT_GNU_ABI_TAG (ABI version tag)
OS: Linux, ABI: 2.6.32		

Displaying notes found at file offset 0x00000274 with length 0x00000024:

Owner	Data size	Description
GNU	0x00000014	NT_GNU_BUILD_ID (unique build ID_
↪bitstring)		
Build ID: df924a2b08a7e89f6e11251d4602022977af2670		

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```
Displaying notes found at file offset 0x002d6c30 with length 0x00000144:
  Owner          Data size      Description
  stapsdt         0x00000031      NT_STAPSDT (SystemTap probe_
↳descriptors)
    Provider: python
    Name: gc__start
    Location: 0x00000000004371c3, Base: 0x0000000000630ce2, Semaphore:_
↳0x00000000008d6bf6
    Arguments: -4@%ebx
  stapsdt         0x00000030      NT_STAPSDT (SystemTap probe_
↳descriptors)
    Provider: python
    Name: gc__done
    Location: 0x00000000004374e1, Base: 0x0000000000630ce2, Semaphore:_
↳0x00000000008d6bf8
    Arguments: -8@%rax
  stapsdt         0x00000045      NT_STAPSDT (SystemTap probe_
↳descriptors)
    Provider: python
    Name: function__entry
    Location: 0x000000000053db6c, Base: 0x0000000000630ce2, Semaphore:_
↳0x00000000008d6be8
    Arguments: 8@%rbp 8@%r12 -4@%eax
  stapsdt         0x00000046      NT_STAPSDT (SystemTap probe_
↳descriptors)
    Provider: python
    Name: function__return
    Location: 0x000000000053dba8, Base: 0x0000000000630ce2, Semaphore:_
↳0x00000000008d6bea
    Arguments: 8@%rbp 8@%r12 -4@%eax
```

The above metadata contains information for SystemTap describing how it can patch strategically placed machine code instructions to enable the tracing hooks used by a SystemTap script.

2 Static DTrace probes

The following example DTrace script can be used to show the call/return hierarchy of a Python script, only tracing within the invocation of a function called “start”. In other words, import-time function invocations are not going to be listed:

```
self int indent;

python$target:::function-entry
/copyinstr(arg1) == "start"/
{
    self->trace = 1;
}

python$target:::function-entry
/self->trace/
{
    printf("%d\t%s:", timestamp, 15, probename);
    printf("%s", self->indent, "");
    printf("%s:%s:%d\n", basename(copyinstr(arg0)), copyinstr(arg1), arg2);
    self->indent++;
}

python$target:::function-return
```

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```
/self->trace/
{
    self->indent--;
    printf("%d\t%s:", timestamp, 15, probename);
    printf("%s", self->indent, "");
    printf("%s:%s:%d\n", basename(copyinstr(arg0)), copyinstr(arg1), arg2);
}

python$target::function-return
/copyinstr(arg1) == "start"/
{
    self->trace = 0;
}
```

It can be invoked like this:

```
$ sudo dtrace -q -s call_stack.d -c "python3.6 script.py"
```

The output looks like this:

```
156641360502280  function-entry:call_stack.py:start:23
156641360518804  function-entry: call_stack.py:function_1:1
156641360532797  function-entry:  call_stack.py:function_3:9
156641360546807  function-return: call_stack.py:function_3:10
156641360563367  function-return: call_stack.py:function_1:2
156641360578365  function-entry: call_stack.py:function_2:5
156641360591757  function-entry:  call_stack.py:function_1:1
156641360605556  function-entry:   call_stack.py:function_3:9
156641360617482  function-return: call_stack.py:function_3:10
156641360629814  function-return: call_stack.py:function_1:2
156641360642285  function-return: call_stack.py:function_2:6
156641360656770  function-entry: call_stack.py:function_3:9
156641360669707  function-return: call_stack.py:function_3:10
156641360687853  function-entry: call_stack.py:function_4:13
156641360700719  function-return: call_stack.py:function_4:14
156641360719640  function-entry: call_stack.py:function_5:18
156641360732567  function-return: call_stack.py:function_5:21
156641360747370  function-return:call_stack.py:start:28
```

3 Static SystemTap markers

The low-level way to use the SystemTap integration is to use the static markers directly. This requires you to explicitly state the binary file containing them.

For example, this SystemTap script can be used to show the call/return hierarchy of a Python script:

```
probe process("python").mark("function__entry") {
    filename = user_string($arg1);
    funcname = user_string($arg2);
    lineno = $arg3;

    printf("%s => %s in %s:%d\n",
        thread_indent(1), funcname, filename, lineno);
}

probe process("python").mark("function__return") {
    filename = user_string($arg1);
    funcname = user_string($arg2);
    lineno = $arg3;
```

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```

printf("%s <= %s in %s:%d\\n",
      thread_indent(-1), funcname, filename, lineno);
}

```

It can be invoked like this:

```

$ stap \
  show-call-hierarchy.stp \
  -c "./python test.py"

```

The output looks like this:

```

11408 python(8274):      => __contains__ in Lib/_abcoll.py:362
11414 python(8274):      => __getitem__ in Lib/os.py:425
11418 python(8274):      => encode in Lib/os.py:490
11424 python(8274):      <= encode in Lib/os.py:493
11428 python(8274):      <= __getitem__ in Lib/os.py:426
11433 python(8274):      <= __contains__ in Lib/_abcoll.py:366

```

where the columns are:

- time in microseconds since start of script
- name of executable
- PID of process

and the remainder indicates the call/return hierarchy as the script executes.

For a `--enable-shared` build of CPython, the markers are contained within the libpython shared library, and the probe's dotted path needs to reflect this. For example, this line from the above example:

```
probe process("python").mark("function__entry") {
```

should instead read:

```
probe process("python").library("libpython3.6dm.so.1.0").mark("function__entry") {
```

(assuming a debug build of CPython 3.6)

4 Available static markers

function__entry(str filename, str funcname, int lineno)

This marker indicates that execution of a Python function has begun. It is only triggered for pure-Python (bytecode) functions.

The filename, function name, and line number are provided back to the tracing script as positional arguments, which must be accessed using `$arg1`, `$arg2`, `$arg3`:

- `$arg1`: (const char *) filename, accessible using `user_string($arg1)`
- `$arg2`: (const char *) function name, accessible using `user_string($arg2)`
- `$arg3`: int line number

function__return(str filename, str funcname, int lineno)

This marker is the converse of `function__entry()`, and indicates that execution of a Python function has ended (either via `return`, or via an exception). It is only triggered for pure-Python (bytecode) functions.

The arguments are the same as for `function__entry()`

line(str filename, str funcname, int lineno)

This marker indicates a Python line is about to be executed. It is the equivalent of line-by-line tracing with a Python profiler. It is not triggered within C functions.

The arguments are the same as for `function__entry()`.

gc__start(int generation)

Fires when the Python interpreter starts a garbage collection cycle. `arg0` is the generation to scan, like `gc.collect()`.

gc__done(long collected)

Fires when the Python interpreter finishes a garbage collection cycle. `arg0` is the number of collected objects.

import__find__load__start(str modulename)

Fires before `importlib` attempts to find and load the module. `arg0` is the module name.

Added in version 3.7.

import__find__load__done(str modulename, int found)

Fires after `importlib`'s `find_and_load` function is called. `arg0` is the module name, `arg1` indicates if module was successfully loaded.

Added in version 3.7.

audit(str event, void *tuple)

Fires when `sys.audit()` or `PySys_Audit()` is called. `arg0` is the event name as C string, `arg1` is a `PyObject` pointer to a tuple object.

Added in version 3.8.

5 SystemTap Tapsets

The higher-level way to use the SystemTap integration is to use a “tapset”: SystemTap’s equivalent of a library, which hides some of the lower-level details of the static markers.

Here is a tapset file, based on a non-shared build of CPython:

```
/*
   Provide a higher-level wrapping around the function__entry and
   function__return markers:
 */
probe python.function.entry = process("python").mark("function__entry")
{
    filename = user_string($arg1);
    funcname = user_string($arg2);
    lineno = $arg3;
    frameptr = $arg4
}
probe python.function.return = process("python").mark("function__return")
{
    filename = user_string($arg1);
    funcname = user_string($arg2);
    lineno = $arg3;
    frameptr = $arg4
}
```

If this file is installed in SystemTap’s tapset directory (e.g. `/usr/share/systemtap/tapset`), then these additional probepoints become available:

python.function.entry(str filename, str funcname, int lineno, frameptr)

This probe point indicates that execution of a Python function has begun. It is only triggered for pure-Python (bytecode) functions.

python.function.return(str filename, str funcname, int lineno, frameptr)

This probe point is the converse of `python.function.entry`, and indicates that execution of a Python function has ended (either via `return`, or via an exception). It is only triggered for pure-Python (bytecode) functions.

6 Examples

This SystemTap script uses the tapset above to more cleanly implement the example given above of tracing the Python function-call hierarchy, without needing to directly name the static markers:

```
probe python.function.entry
{
    printf("%s => %s in %s:%d\n",
           thread_indent(1), funcname, filename, lineno);
}

probe python.function.return
{
    printf("%s <= %s in %s:%d\n",
           thread_indent(-1), funcname, filename, lineno);
}
```

The following script uses the tapset above to provide a top-like view of all running CPython code, showing the top 20 most frequently entered bytecode frames, each second, across the whole system:

```
global fn_calls;

probe python.function.entry
{
    fn_calls[pid(), filename, funcname, lineno] += 1;
}

probe timer.ms(1000) {
    printf("\033[2J\033[1;1H") /* clear screen */
    printf("%6s %80s %6s %30s %6s\n",
           "PID", "FILENAME", "LINE", "FUNCTION", "CALLS")
    foreach ([pid, filename, funcname, lineno] in fn_calls- limit 20) {
        printf("%6d %80s %6d %30s %6d\n",
               pid, filename, lineno, funcname,
               fn_calls[pid, filename, funcname, lineno]);
    }
    delete fn_calls;
}
```